

# The Narrow-Line Regions of LINERs as Resolved with the *Hubble Space Telescope*<sup>1</sup>

Richard W. Pogge

Department of Astronomy, The Ohio State University, 140 W. 18th Ave., Columbus, OH 43210-1173

Dan Maoz

School of Physics & Astronomy and Wise Observatory, Tel-Aviv University, Tel-Aviv 69978, Israel

Luis C. Ho

Carnegie Observatories, 813 Santa Barbara St., Pasadena, CA 91101

and

Michael Eracleous

Department of Astronomy and Astrophysics, The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802

## ABSTRACT

Low-ionization nuclear emission-line regions (LINERs) exist in the nuclei of a large fraction of luminous galaxies, but their connection with the active galactic nucleus (AGN) phenomenon has remained elusive. We present *Hubble Space Telescope* (*HST*) narrowband ( $[\text{O III}]\lambda 5007$  and  $\text{H}\alpha + [\text{N II}]$ ) emission-line images of the central regions of 14 galaxies with LINER nuclei. This is the first such study of a sizable sample of LINERs at *HST* resolution. The compact,  $\sim 1''$ -scale, unresolved emission which dominates the line flux in ground-based observations of these LINERs is mostly resolved in the *HST* images. The bulk of the  $\text{H}\alpha$  and  $[\text{O III}]$  emission comes from regions with sizes of tens to hundreds of parsecs. The resolved emission comes from a combination of knots, filaments, and diffuse gas whose morphology differs from galaxy to galaxy. Most of the galaxies do not show clear linear structures or ionization cones analogous to those often seen in Seyfert galaxies. An exception is NGC 1052, the prototypical LINER, in

---

<sup>1</sup>Based on observations with the *Hubble Space Telescope* which is operated by AURA, Inc., under NASA contract NAS 5-26555.

which we find a  $3''$ -long ( $\sim 250$  pc) biconical structure that is oriented on the sky along the galaxy’s radio jet axis. M84 also shows signs of possible biconical gas structures. Seven of the galaxies have been shown in previously published *HST* images to have a bright compact ultraviolet (UV) nuclear source, while the other seven do not display such a central UV source. Our images show a dusty environment in the nuclear region of all 14 galaxies, with clear indications of obscuration of the nuclei in most of the “UV-dark” cases. The data thus suggest that the line-emitting gas in most LINERs is photoionized by a central source (which may be stellar, nonstellar, or a combination thereof) but that this source is often hidden from direct view in the UV by dust in the host galaxy. We find no obvious differences between the morphologies of the nine “LINER 1.9s” with detected weak broad  $H\alpha$  wings in their spectra and the morphologies of the other five objects. Likewise, there is no clear distinction in morphology between objects whose UV spectra are dominated by hot stars (e.g., NGC 4569) and those that are more AGN-like (e.g., NGC 4579).

*Subject headings:* galaxies: active — galaxies: ISM — galaxies: nuclei — galaxies: Seyfert

## 1. Introduction

Nuclear activity in galaxies, which finds its most dramatic expression in quasars, also appears in systems with much lower luminosities. Many galactic nuclei exhibit broad  $H\alpha$  emission lines which, while much weaker, are nonetheless qualitatively similar to those observed in quasars (Stauffer 1982; Keel 1983b; Filippenko & Sargent 1985; Ho et al. 1997b). A significant fraction of emission-line objects, which may be physically related to AGNs, are galaxies containing low-ionization nuclear emission-line regions (LINERs; Heckman 1980; see the reviews included in Eracleous et al. 1996). LINERs, present in over 30% of all galaxies and in 60% of Sa–Sab spirals with  $B \leq 12.5$  mag (Ho, Filippenko, & Sargent 1997a), could thus represent the low-luminosity end of the AGN phenomenon. In fact, about 15%–25% of LINERs have a broad component in the  $H\alpha$  line — the “type 1.9” LINERs — similar to the fraction in Seyferts (Ho et al. 1997b). Recently, Barth, Filippenko & Moran (1999a, b) have shown that some LINERs have weakly polarized broad emission lines, analogous to the polarized broad lines from the “hidden broad-line region” of some Seyfert 2 galaxies (e.g., Antonucci & Miller 1985). However, unlike Seyfert nuclei and QSOs, whose enormous luminosities and rapid variability argue for a nonstellar energy source, the luminosities of LINERs are sufficiently low that one cannot unambiguously

associate them with AGNs of higher luminosities. For example, stellar energy sources are plausible both on energetic and spectroscopic grounds (e.g., Terlevich & Melnick 1985; Filippenko & Terlevich 1992; Shields 1992; Maoz et al. 1998). The potential role of LINERs in constituting the faint end of the AGN luminosity function is important for understanding the nature of AGNs, their evolution, and their contribution to the X-ray background.

To address some of the above issues, Maoz et al. (1995) obtained ultraviolet (UV; 2300 Å) images of an unbiased selection from a complete sample of nearby galaxies with the *Hubble Space Telescope* (*HST*) Faint Object Camera (FOC). They discovered that 6 out of 25 LINERs in the sample contain unresolved ( $< 0''.1$ , or  $< 1 - 2$  pc) nuclear UV emission sources. A similar result was found by Barth et al. (1998), using UV images taken with the Wide-Field Planetary Camera 2 (WFPC2) on *HST*. The extreme-UV emission from such sources may provide some or all of the energy required to produce the nuclear emission lines by photoionization. More specifically, Maoz et al. (1998) showed that in three out of seven UV-bright LINERs, the extreme-UV flux, based on a reasonable extrapolation from the UV, is sufficient to account for the observed  $H\alpha$  flux. In the other four objects, the extreme-UV flux is deficient by a factor of a few, but these four objects have X-ray/UV flux ratios 100 times larger than the previous three, which suggests that there is much more flux in the extreme-UV than a simple extrapolation from the UV would indicate. This suggestion is also supported by the spectral energy distributions of LINERs and low-luminosity AGNs presented by Ho (1999). Any mild foreground extinction would alleviate the deficit even further. It is thus plausible to conclude that the line-emitting gas of UV-bright LINERs is powered by photoionization.

The 6 UV-bright and 19 UV-dark LINERs studied by Maoz et al. (1995) are otherwise similar in terms of spectral line ratios and overall emission-line luminosities. A nuclear UV source may therefore exist in all LINERs, but may be obscured by dust in 75% of the objects. Alternatively, Eracleous, Livio, & Binette (1995) have suggested that the emission lines are produced in response to a variable continuum that is in its “off” state with a 25% duty cycle (due, perhaps, to sporadic tidal disruption and accretion of individual stars by a central black hole). Another possibility is that the emission lines in UV-dark LINERs are produced in shocked, rather than photoionized, gas (Koski & Osterbrock 1976; Fosbury et al. 1978; Heckman 1980; Dopita & Sutherland 1995), thus accounting for the absence of a central, point-like UV source. Moreover, the UV-bright LINERs are not necessarily AGNs, as the UV sources could be hot star clusters. Indeed, UV spectroscopy with the *HST* has shown that, while some LINERs may be AGNs (Ho et al. 1996; Barth et al. 1996), the UV emission in other UV-bright LINERs is clearly dominated by massive stars (Maoz et al. 1998). Interestingly though, there is not a clear correspondence between the existence of a point-like nuclear UV source and the detection of broad  $H\alpha$  wings in the spectrum, as is

the case in most Seyfert 1s.

An independent source of information comes from the X-ray band, where the morphologies and spectra of LINERs suggest that some of them could harbor low-luminosity AGNs. Published and archival X-ray images of LINERs with high angular resolution ( $5''$ – $8''$ ), taken with the *Einstein* and *ROSAT* HRIs (e.g., Fabbiano, Kim, & Trinchieri 1992; Koratkar et al. 1995), show a wide variety of X-ray morphologies: point sources, with or without a surrounding halo, and diffuse sources, which do not seem to be related to the UV morphology. The 0.5–10 keV spectra of LINERs obtained with *ASCA* can generally be fitted by a linear combination of a Raymond-Smith plasma model ( $kT \approx 0.6 - 0.8$  keV) and an absorbed (column densities in excess of  $10^{21}$  cm $^{-2}$ ) hard component. The soft, thermal plasma emission is usually attributed to circumnuclear hot gas. In the case of LINER 1.9s, the hard component is well fitted by a power law with photon indices  $\Gamma \approx 1.7$ – $2.0$  (e.g., Serlemitsos, Ptak, & Yaqoob 1996; Ptak et al. 1999; Awaki 1999; Terashima 1999; Ho et al. 1999), as seen in luminous Seyfert 1s (Nandra et al. 1997), and the emission has a compact, spatially unresolved morphology within the coarse angular resolution of *ASCA* (FWHM  $\approx 3'$ ). Where higher resolution *ROSAT* HRI images are available, a central compact core is seen in the soft X-rays as well. These characteristics strengthen the case that LINER 1.9s are genuine AGNs. The situation for LINER 2s is more complicated. Terashima et al. (1999) have recently analyzed *ASCA* observations of a small sample of LINER 2s, and they find that the hard component, while consistent with a power law with  $\Gamma \approx 2$ , can also be represented by a thermal bremsstrahlung model with a temperature of several keV. Moreover, the emission in the hard band is seen to be extended on scales of several kpc, consistent with a population of discrete sources such as low-mass X-ray binaries. Terashima et al. also show that, based on an extrapolation of their absorption-corrected X-ray fluxes into the UV, there is perhaps insufficient power to drive the luminosities of the optical emission lines. These findings suggest that either LINER 2s do not contain an AGN or that the AGN component, if present, must be heavily obscured by matter with a column density much greater than  $10^{23}$  cm $^{-2}$ .

Another important tool for studying AGNs, which we employ here, is narrowband, emission-line imaging of the nuclear regions. Narrowband imaging of Seyfert 1 and 2 nuclei has revealed, in some cases, striking ionization cones emerging from the active nuclei and well aligned with the axes of the radio jets (Haniff, Wilson, & Ward 1988; Pogge 1989a; Wilson & Tsvetanov 1995). This technique produces spectacular results when combined with the angular resolution of *HST* (e.g., NGC 5728, Wilson et al. 1993). The ionization structure of the narrow-line region gas, as revealed by such studies, gives complementary information to that provided by single-aperture spectra. Ground-based narrowband imaging of LINERs by Keel (1983a) and by Pogge (1989b) has shown that they are distinct

from Seyferts in their circumnuclear emission, at least when probed on the same ( $\sim 1''$ ) angular scale. At these scales, some LINERs have faint diffuse emission, as opposed to the linear structures in many Seyferts, and the emission is usually dominated by a compact, marginally resolved nuclear region. Resolving the nuclear structures of LINERs can provide further clues to their relation to AGNs. The small scales and faintness of these structures relative to the bright host-galaxy background mean that the capabilities of *HST* are needed for this task. To this end we have carried out a study of the narrow-line regions of LINERs using narrowband [O III]  $\lambda 5007$  and  $H\alpha + [\text{N II}]$  WFPC2 images of 14 objects. The results of our study are the subject of this paper. In §2 we describe the observations and the data reduction. In §3 we present the final images and measurements and we discuss them in §4. Finally, in §5 we summarize the results and present our conclusions. Throughout this paper we assume a Hubble constant of  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

## 2. Observations and Reduction

The galaxies we have chosen for narrowband imaging with *HST* represent the two classes of LINERs, UV-bright and UV-dark, that have been identified in previous *HST* UV observations (Maoz et al. 1995; Barth et al. 1998). They were selected on the basis of their bright, high-contrast  $H\alpha$  lines, as determined from spectra and narrowband images obtained from the ground. We have supplemented these data with archival images of eight other galaxies, classified as LINERs by Ho et al. (1997a), and observed with WFPC2 using the same narrowband filters. In Table 1 we list the galaxies included in our collection, and we summarize their basic properties. We emphasize that these galaxies do not constitute a statistically well-defined sample, but rather a random selection of LINERs with relatively strong emission lines. At any rate, this is the first time that the spatial structure of the narrow-line region is studied at *HST* resolution for a sizable number of such objects.

The galaxies were imaged with WFPC2, generally with the nucleus positioned on the PC CCD, which has a scale of  $0''.0455 \text{ pixel}^{-1}$ . In the case of NGC 3031 the nucleus was positioned on the WF3 CCD, whose scale is  $0''.10 \text{ pixel}^{-1}$ . Table 2 summarizes the observations of each galaxy, gives the filters used, their corresponding exposure times, and the observing programs under which the observations were carried out. All the galaxies were observed through either the F656N or the F658N filters, in order to sample the  $H\alpha + [\text{N II}]$  complex at the proper redshift. Images through the F502N filter, which covers the [O III] $\lambda 5007$  line, exist for only five of these galaxies with sufficient integration time to be useful. Broad- and medium-band images of each galaxy were also obtained, as detailed in Table 2, and used for continuum subtraction and derivation of color maps. For NGC 1052,

whose narrowband image was obtained from the *HST* archive, no broad-band images are available. However, the extended line emission in this object is strong enough that it can be seen even without continuum subtraction. In fact, this is the only object in which, after some additional image processing, we find an unambiguous ionization cone, analogous to those seen in Seyferts (see §3).

All of the WFPC2 images used in this study were processed by the standard STScI OPUS pipeline (described by Biretta et al. 1996), and required only minimal post-processing to combine multiple images, correct for saturated pixels, and remove cosmic rays. We present only the WFPC2 PC1 detector images since the nuclei of the galaxies were centered on this CCD. The exception is NGC 3031 (M81), for which the archival images had the nucleus centered on the WF3 detector. For the targets in our own observing program (GO-6436), continuum images were acquired as two pairs of short and long integrations. If the object was particularly bright, an additional, 6 s integration was also obtained. The short-exposure images were used to correct for saturated pixels in the long-exposure images. Our narrowband images were acquired as two or three long integrations, since saturation was not expected to be a problem.

For pairs or triplets of images of the same integration time, we combined the images using a statistical differencing technique implemented as an *XVista* command script (Pogge & Martini 1999). This technique is as follows. The difference image, formed by subtracting one image in a pair from the other, consists primarily of positive and negative cosmic-ray hits, as the galaxy, foreground stars, and background, all cancel to within the noise. All pixels within  $\pm 5\sigma$  of the mean residual background level on the difference image are then set to zero (tagging them as unaffected by cosmic rays), and a pair of cosmic-ray templates are derived by separating the remaining positive and negative pixels. These templates are then subtracted from the original images, and the two cosmic-ray subtracted images are added together to form the final galaxy image. When three images are available, all pair-wise combinations are used to generate the templates. In all cases, the statistical differencing method produced superior cosmic-ray rejection compared to standard tasks (e.g., *CRREJ* in *STSDAS*), and it is computationally much faster.

Archival data sets with pairs of images were processed in the same way. In a few cases, however, only single integrations were available, and the cosmic ray hits were removed manually, using the interactive *TVZAP* routine in *XVista*. When the archival images pairs had unequal integration times (e.g., for NGC 404, 500s and 1200s for the F656N filter), we scaled the long integration to the shorter one and applied the differencing method, followed by additional manual cleaning. The resulting image cleaning is not as thorough as with well-matched integration times, but it still is better than the other algorithms we tried.

In all of our images, the mean intensity level of the background sky is negligible (a few counts at most). This was estimated by examining the outskirts of one of the WF frames without much galaxy light in it, and computing a modal sky level in reasonably clear regions. The combined on-band emission-line and off-band continuum images were converted to units of flux density per pixel, based on the May 1997 updated photometry values for each filter for the PC detector.

Continuum-subtracted emission-line images were created by subtracting the associated continuum-band images. In a few cases, it was clear that our background estimate was in error (it left either positive or negative fields of pixels), and so we refined the continuum estimation and iterated. The final continuum-subtracted images were left in units of flux density per pixel. For several archival data sets, the continuum images had to be registered and/or rotated to match the narrowband images. This presented no problem, and standard *XVista* tools were used (the procedure is analogous to the one described in Pogge 1992).

Color maps were generated for all six of our GO program images by converting flux density per pixel into standard Johnson/Cousins magnitudes using the transformations derived by Holtzman et al. (1995), and then dividing the two images. For NGC 4192 and NGC 4569, we had both F547M and F791W image pairs from our own program as well as archival F555W and F814W images, so we could verify the conversion between these bands and estimates of the  $(V - I)$  colors. We were careful to register the original on-band and off-band images so that we could later directly compare our emission-line and color maps. We use these below to study the associations between the emission-line regions and the patches of dust and star clusters in the galaxies. For the LINERs for which we have only archival images, we could create  $(V - I)$  color maps for three galaxies (NGC 3998, NGC 4374, and NGC 4594).

For four galaxies with F547M images and no corresponding red broad-band image (NGC 3031, 4486, 4036, and 4258), we were able to map the distribution of dust using an “unsharp masking” technique described by Pogge & Martini (2000). In brief, an unsharp mask for an image was created by smoothing the original F547M image with a model PSF image computed using TinyTim (Krist & Hook 1997). The  $(\text{Image} \otimes \text{PSF})$  convolution was carried out in the Fourier domain using an *XVista* command script. The original image was then divided by the smoothed image to form a normalized residual image in which dusty features appear as negative residuals, and emission or stars appear as positive residuals. Using this technique on F547M images of galaxies for which we have  $V - I$  color maps shows that the normalized unsharp residual images can retrieve all of the dust structures seen in the color maps.

### 3. Results

#### 3.1. Images and Measurements

Figures 1a–e show our reduced narrowband images and dust maps. For each galaxy in Figure 1a–d we show the continuum-subtracted  $H\alpha + [N II]$  PC1 image on the left, and on the right show either the  $(V - I)$  color map, or an unsharp residual map of the F547M image if there was no second broadband filter image. In both the  $V - I$  and the F547M unsharp mask images darker shades denote the regions of dust absorption. Each panel of these figures shows a  $10'' \times 10''$  segment of the image centered on the nucleus (oriented with North up and East to the left), and with a scale bar in the lower left corner of each emission-line image showing 100 pc projected at the galaxy’s distance (see Table 1). The contrast of the emission-line images is chosen to emphasize the faint circumnuclear emission regions. Figure 1e shows our images of NGC 3031 which, unlike the others, is on the WF3 detector. Here we show  $H\alpha + [N II]$  emission on the left, and the unsharp residual map of the F574M filter image on the right for the central  $30''$  of this galaxy. The scale bar on the lower left shows 100 pc at the distance of NGC 3031 (Table 1). Figure 2 shows on the left the original F658N image (i.e., without continuum subtraction) of NGC 1052, with a normalized unsharp residual map of the same on the right. This residual map shows emission as bright and absorption (presumably dust) as dark. Each panel shows the inner  $15''$  of NGC 1052, and the scale bar indicates 100 pc. The axis of the VLA radio jet (Wrobel 1984) is shown as a dashed line.

Figures 3a and 3b show the continuum-subtracted  $[O III] \lambda 5007$  images for the 5 galaxies for which these data are available. In Figure 3a, we pair  $[O III] \lambda 5007$  emission-line images with “excitation maps” of the  $H\alpha + [N II]/[O III] \lambda 5007$  ratio for NGC 4258, NGC 4579, and NGC 5005. Although noisy, these maps do not reveal any clear high-excitation knots with the exception of NGC 4258. Here we see relatively-highly excited gas in a segment of the braided jet that lies to the north of the nucleus in our images (Cecil, Wilson, & Tully 1992; Cecil, Wilson, & DePree 1995; Cecil, Morse, & Veilleux 1995). Figure 3b shows only the continuum-subtracted  $[O III]$  images for the remaining two galaxies, NGC 4192 and NGC 4569. The excitation maps constructed for these galaxies are extremely noisy due to the low signal-to-noise ratio in the  $[O III]$  images, and only total fluxes in synthetic apertures can be measured with any confidence (see Table 3). Overall, the entire resolved emission-line regions of these LINERs seem to be in a low-ionization state.

We have measured the integrated emission-line fluxes through various apertures, separating the nuclear and circumnuclear contributions. These measurements are summarized in Table 3. Circular apertures were used, except in the cases of NGC 4192 and



NGC 5005, where rectangular apertures were used to avoid strong dust lanes (in both) and H II regions (in NGC 4192). Since NGC 4192 and NGC 5005 have no discernible nuclei in their narrowband images, the nuclear fluxes were estimated in apertures centered using the brightness peaks in their F791W continuum images. Table 3 gives “band” fluxes, without an attempt to convert to emission in a particular line by correcting for the filter transmission of other lines in the bandpasses (i.e., [O III]  $\lambda$ 4959 and [N II]  $\lambda\lambda$ 6548, 6583).

In the next section we describe the main features of the images of individual galaxies. We refer to an object as being “UV-bright” if space-UV observations (generally the *HST*/FOC F220W images of Maoz et al. 1995) have revealed a bright compact nuclear UV source in the galaxy. We will base the optical spectral classification of these objects on Ho et al. (1997a), and follow their terminology, where a “LINER 2” is a LINER without detected broad H $\alpha$  wings, a “LINER 1.9” is a LINER that does have such weak broad wings, and a “transition object” is one whose optical narrow emission-line ratios are intermediate between those of a LINER and an H II nucleus. Data on these properties are also summarized in Table 1.

### 3.2. Individual Objects

#### NGC 404

This is a UV-bright LINER 2, whose UV spectrum has a significant contribution from massive stars (Maoz et al. 1998). In the *HST* emission-line images, much of the nuclear emission appears as a hollow one-sided fan extending into filamentary wisps at distances of 5'' or more from the nucleus. These wisps are reminiscent of gaseous structures blown out by supernovae, which are expected, given that the spectrum of this object is dominated by hot stars. There is also one bright point source 0''.16 north of the nucleus, possibly a planetary nebula or a compact H II region. It is not obviously associated with a secondary UV source seen in the FOC image of this galaxy. The nuclear region is dusty, but has a blue nucleus, suggesting the nucleus itself is unobscured.

The distance to this galaxy is controversial, as discussed in detail by Wiklind & Henkel (1990). The distance we have adopted in Table 1 is Tully’s (1988) value of 2.4 pc (for  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ), which was assigned based on NGC 404’s probable membership in his so-called “14+12” group. On the other hand, the CO observations of Wiklind & Henkel (1990) can only be reconciled with other observational data if the distance is 10 Mpc. The *I*-band (F814W) image shows the galaxy beginning to be resolved into stars (the brightest giants are apparently visible). If so, then our measurements favor the shorter distance.

## NGC 1052

This galaxy is often considered to be the prototypical LINER, with weak broad  $H\alpha$  wings that give it a LINER 1.9 classification (Ho et al. 1997a). The broad wings have recently been shown by Barth et al. (1999a) to be preferentially polarized relative to the narrow lines and the continuum, suggesting the presence of a hidden broad-line region that is seen in scattered light. Recent *HST* observations (Allen, Koratkar, & Dopita 1999; Gabel et al. 1999) show the UV-bright nucleus has a UV–optical spectrum consisting of narrow lines on top of a featureless continuum. The archival  $H\alpha+[N\ II]$  F658N WFPC2 image presented here shows a collimated, conical structure emerging from a compact core. The high surface-brightness line emission is evident in the original image even though we do not have a broad-band image to perform continuum subtraction. The biconical nature of the structure is most clearly brought out in the normalized unsharp residual map of the image (Figure 2b), which reveals the rear (west) side of the cone. Together with M84 (see below), these are the only objects among the LINERs imaged which show a clear indication of a Seyfert-like emission-line cone. The cone’s axis is at position angle  $96^\circ$  with a full opening angle of about  $70^\circ$ . This corresponds roughly to the axis of the radio lobes observed in this galaxy (Wrobel 1984), and is similar to the alignment generally found in Seyferts. Our result thus adds another AGN characteristic to this LINER. We also note that there are two faint knots of emission straddling the nucleus, about  $5''$  from it, along a position angle of  $81^\circ$ .

## NGC 3031 (M81)

Detailed modeling of the narrow- and broad-line spectrum of this object (Ho et al. 1996) clearly shows that the line-emitting gas has the low-ionization state expected of LINERs, even if the measured  $[O\ III]/H\beta$  ratio technically places it in the Seyfert class (Ho et al. 1997a). The UV spectrum (Ho et al. 1996; Maoz et al. 1998) consists of broad, AGN-like, emission lines superposed on a featureless continuum. Devereux, Ford, & Jacoby (1997) have already presented the  $H\alpha+[N\ II]$  data shown here, and have also shown that the galaxy possesses a UV-bright nucleus. The  $H\alpha+[N\ II]$  emission comes mostly from a bright compact source, surrounded by symmetric, disk-like, diffuse emission (Figure 1e, left). The unsharp-residual processed image (Figure 1e, right) shows a spiral-like dust lane extending  $\sim 12''$  north of the nucleus. The major axis of the disk is at a position angle of  $18^\circ$  and has a minor-to-major axis ratio of 0.78. It extends up to about  $5''$  from the center, while faint, filamentary structure is visible out to  $8''$ .

### NGC 3718

This is a UV-dark LINER 1.9. The emission in the *HST* narrowband images is dominated by a strong point source, surrounded by some diffuse circumnuclear  $H\alpha$  emission. The diffuse emission is brighter on one side. The  $V - I$  image shows the nucleus is clearly very dusty and likely obscured. This is not surprising given its very red optical spectrum (Ho et al. 1995).

### NGC 3998

This LINER 1.9 has been shown to be UV-bright by Fabbiano, Fasnacht, & Trinchieri (1994). Ultraviolet spectra from *HST* do not exist, to date. The  $H\alpha + [N II]$  image shows a 100-pc disk-like structure surrounding a compact nucleus. The major axis of this disk is oriented along a position angle of  $90^\circ$  with a length of  $3''$ , while the minor axis length is  $2''$ . The  $V - I$  map shows little indication of dust in the nuclear region.

### NGC 4036

This LINER 1.9 is UV-dark, based on WFPC2 F218W images (Barth et al. 1998). Its  $H\alpha + [N II]$  image has a complex filamentary and clumpy structure, with several “tentacles” extending up to  $4''$  northeast of the nucleus along a position angle of  $70^\circ$ . The nucleus proper resembles an ellipse with a major axis of  $0''.6$  along a position angle of  $45^\circ$ . The unsharp-masked F547M image reveals wisps of dust in a disk-like configuration surrounding the nucleus on all scales probed. This is one of the few LINERs in our sample whose emission-line morphology can possibly be termed “linear” in some sense, but it seems that this morphology is in the plane of the inclined dusty disk, rather than perpendicular to it.

### NGC 4192 (M98)

This object has been classified by Ho et al. (1997a) as a “transition object,” one whose optical spectrum is intermediate between that of a LINER and an H II nucleus. It appears dark in UV images. In the *HST* emission-line images, the nucleus is resolved into knots spanning  $0''.5$  in an east-west direction. In the continuum images the nucleus appears “soft”, rather than having a sharp point source like NGC 4569. The  $V - I$  map shows nuclear region is dusty and the nucleus probably obscured. On larger scales, there is a ring of H II

regions, partially obscured by dust, and already seen in the ground-based images of Pogge (1989b).

### NGC 4258 (M106)

This galaxy contains the famous masing disk (Watson & Wallin 1994; Miyoshi et al. 1995) whose Keplerian rotation provides some of the best evidence for a massive black hole in a galactic nucleus. It has variably been classified as a LINER or a Seyfert 1.9, and is another example of a borderline case. Wilkes et al. (1995) and Barth et al. (1999c) have shown that the spectrum in polarized light has emission lines that are broader than the lines in the total flux spectrum. However, this is seen not only in the Balmer lines but in most of the forbidden lines as well, with the width of the lines in the polarized spectrum depending on the critical density of the transition. The phenomenon is thus different from that of the hidden broad-line regions revealed in polarized light in some Seyfert 2 galaxies.

A WFPC2 F218W image taken by Ho et al. (2000a) shows no conspicuous UV nucleus. We therefore aligned the brighter O/B star knots on the F218W image with those in an archival F300W image of this galaxy. We detect 2180 Å flux from all the blue stars easily visible in the F300W and F547M images (see Figure 4). We then find that a “nucleus” *per se* is visible in the F218W image, but it is weak and its contrast low compared to its surroundings. Translation of the nuclear count rate to a UV flux is not straightforward, because of the large time fluctuations in the UV sensitivity of WFPC2, plus the proneness of the F218W filter to red leaks when observing such obviously-red sources. The UV flux for this nucleus, which we list in Table 1, accounts for neither effect and must therefore be treated as uncertain. In any case, it is clear the flux is quite low compared with the UV-bright objects in our sample. It is reasonable to treat this nucleus as intermediate, between UV-bright and UV-dark.

The emission-line images show a compact core and a spiral feature emerging to the north (extending up to 5'' from the nucleus) which could be the base of the helical emission-line jet seen on larger scales by Cecil, Wilson, & Tully (1992). Thus, this may be considered another LINER with collimated (or at least organized) narrow-line emission. Although there is ample evidence for circumnuclear dust in the images, there is no dust that obviously covers the nucleus in the unsharp-masked F547M image. This is confirmed also in “ $U - V$ ” image we have formed using the F330W and F547M images. Since the masing molecular gas disk is viewed nearly edge-on (Miyoshi et al. 1995), with significant optical depth along the line of sight to the nucleus, perhaps it is the dust in this disk itself that is partially obscuring the nucleus in the UV, and thus making it appear so weak.

### NGC 4374 (M84)

The LINER 2 nucleus of this galaxy is UV-dark, based on FOC F220W imaging by Zirbel & Baum (1998). M84 has a nonthermal, flat-spectrum radio core and compact X-ray emission (see discussion in Ho 1999), and its nucleus has recently been found to contain a massive compact dark object, presumably a supermassive black hole (Bower et al. 1998). The  $H\alpha + [N II]$  data have been previously presented by Bower et al. (1997). The images show an inclined gas disk surrounding the nucleus. Our  $V - I$  map clearly shows that the nucleus is covered by a thick dust lane. Bower et al. (1997) also argued for the possible presence of an ionization cone that is roughly aligned with the radio structure in this object (Birkinshaw & Davies 1985), but we find the case for such a cone is not clear. At the very least, it is not an obvious morphological structure in the extended  $H\alpha$  emission-line gas (Figure 1c, top left panel). This structure takes the form of filaments that extend roughly east-west and north-south, along position angles  $85^\circ$  and  $0^\circ$ . The east-west complex extends  $5''$  east and  $3''$  west of the nucleus, while the north-south complex extends  $2''$  north and south of the nucleus.

### NGC 4486 (M87)

This LINER 2, a giant elliptical galaxy in the Virgo cluster, is well known for its collimated jet seen at radio, optical, and UV wavelengths. Both the jet and the dynamical evidence for a supermassive black hole (Sargent et al. 1978; Harms et al. 1994; Macchetto et al. 1997) testify to the existence of an AGN. The nucleus is UV-bright (Boksenberg et al. 1992; Maoz et al. 1996). Recent UV spectroscopy of the nucleus with *HST*/FOS (Sankrit, Sembach, & Canizares 1999) and *HST*/STIS (Ho et al. 2000b) reveals emission lines of width  $\sim 3000 \text{ km s}^{-1}$  on top of a featureless continuum. The  $H\alpha + [N II]$  image was previously published by Ford et al. (1994). It shows a compact disk with a major axis of length  $0''.77$  along position angle  $0^\circ$ , and a minor axis of length  $0''.59$ . The disk is surrounded by wispy filaments extending in various directions up to  $10''$  from the nucleus. It is noteworthy that the optical jet, which is conspicuous in the raw data (and also visible in the unsharp residual map in Figure 1c), disappears completely in the continuum-subtracted image, indicating very little line emission from the jet itself. The unsharp residual map also shows very little evidence of nuclear dust.

### NGC 4569 (M90)

This galaxy has a bright, point-like nucleus at optical and UV bands, with a LINER 2 optical spectrum. Maoz et al. (1998) have shown that the UV spectrum is dominated by massive stars. The new *HST* images show an unresolved nucleus in both continuum and emission lines. The nucleus dominates the emission. On larger scales, there is a disk or spiral-arm-like structure in the  $H\alpha$  image, extending up to  $2''$  from the nucleus in the north-south direction (position angle  $4^\circ$ ). Similar structures are seen in [O III] although they are not as well defined. The  $V - I$  map shows that, while the circumnuclear region is dusty, the nucleus itself is apparently unobscured by dust.

### NGC 4579 (M58)

This is a LINER 1.9 galaxy with many AGN characteristics (Filippenko & Sargent 1985; Barth et al. 1996; Ho et al. 1997b; Maoz et al. 1998; Terashima et al. 1998). The  $H\alpha$  emission is dominated by a nuclear point source, but is surrounded by complex clumpy and filamentary emission. The overall complex has an elliptical shape with a major axis of length  $2''$  along position angle  $120^\circ$  and a minor axis of length  $1''$ . The filamentary emission may be likened to a shell or a ring (perhaps part of a disk) with a dark lane going across it. A similar structure is seen in [O III], although the signal-to-noise ratio is lower. The  $V - I$  image shows that, while the filaments are associated with circumnuclear dust, the nucleus appears to be unobscured.

### NGC 4594 (M104)

The “Sombrero” galaxy has a LINER 2 nucleus which may be, like NGC 4258, borderline between UV-bright and UV-dark. Crane et al. (1993) have shown that the nucleus appears unresolved and isolated in *HST* images at  $3400 \text{ \AA}$ . However, the *HST*/FOS UV spectrum of this galaxy, analyzed by Nicholson et al. (1998) and Maoz et al. (1998), shows shortward of  $3200 \text{ \AA}$  a red continuum falling with decreasing wavelength, and becoming dominated by scattered light within the spectrograph below around  $2500 \text{ \AA}$ . In Table 1 we quote the flux density measured by Maoz et al. (1998) from this spectrum, but because of the scattered light contamination and the lack of a UV image, we regard the quoted flux density as an upper limit to the true value. Due to the low signal-to-noise ratio of the UV spectrum, the nature of the UV light source (stars or AGN) is ambiguous. Fabbiano & Juda (1997) observed this galaxy with the *ROSAT*/HRI and detected a

point-like soft X-ray source coincident with the nucleus but noted that the source could be highly absorbed. The  $H\alpha + [\text{N II}]$  image shows “S”-shaped wisps emerging from a bright, compact, possibly disk-like  $H\alpha$  core. The two wisps extend up to  $4''$  east and west and up to  $1''$  south of the nucleus. The  $V - I$  image shows that the dust generally follows the  $H\alpha$  morphology, but with the nucleus behind a dust lane.

## NGC 5005

This is a LINER 1.9, which is dark in UV images. In the new *HST* images, the line emission is distributed in a number of compact clumps within  $1''$  of the nucleus. These are surrounded by fan-shaped filaments and diffuse emission extending up to  $3''$  southeast of the nucleus. The emission-line and  $V - I$  images both show clearly that the nucleus is obscured. In an attempt to identify whether the emission-line clumps are associated with individual stars or star clusters, we have tried to align the  $H\alpha + [\text{N II}]$  image with the FOC 2200Å image of Maoz et al. (1996). We find no unique registration that will align all the major H II regions and the UV knots in a region  $10''$  south of the nucleus, and no registration that can align the nuclear UV and  $H\alpha$  knots. It thus appears that here, as in the other galaxies, the line-emitting gas is dusty, causing the UV and  $H\alpha$  emission to be mutually exclusive. As a consequence, we cannot answer conclusively the question of whether, in this galaxy, there is direct evidence for the excitation of the emission-line gas by hot stars.

## 4. Discussion

With the information given above, we are in a position to address some of the following questions.

1. Do any of the LINERs, when observed at *HST* resolution, show ionization cones or linear structures analogous to those seen in Seyferts? If so, what are their general characteristics (e.g., opening angles, linear extent, excitation level)? Ionization cones (or lobes) are probably the best evidence for obscuration of the nucleus by a toroidal structure, which would account for the absence of a nuclear UV source in UV-dark LINERs.
2. Is there a difference in the morphology of the ionized gas in the circumnuclear regions of UV-bright and UV-dark LINERs? Differences in morphology can afford direct tests of competing scenarios, as follows:

- (a) *Obscuration:* The nuclear UV source could be hidden by a toroidal structure, as detailed above, or with patchy foreground obscuration by circumnuclear dust (e.g. van Dokkum & Franx 1996), not necessarily associated with the nucleus itself.
- (b) *An ionizing continuum source temporarily in its “off” state:* The duty-cycle hypothesis of Eracleous et al. (1995) predicts a spatial gap between the nucleus and the ionization front in the [O III]-emitting region because of rapid recombination of the  $O^{+2}$  ion. In contrast, the long recombination time scale of the ionized zone implies that its corresponding gap should be unobservable across the narrow-line region. The recurrence time of active phases of the nuclear source in this scenario is of order a century. In view of the distances of these galaxies the implied angular size of a typical [O III] ring would be around  $0.''6$ , well within the resolution of these *HST* images.
- (c) *Shock excitation of the emission-line gas:* This could manifest itself as filamentary and bow-shaped structures indicative of shock fronts. The emission-line images can be particularly informative at scales of a few arcseconds where the high angular resolution of the *HST* and the often-seen clumpiness of line-emitting gas can reveal faint line-emitting structures that are undetectable from the ground.

First, we find that only one of the LINER nuclei observed, NGC 1052, shows an unambiguous ionization cone of the kind often seen in Seyfert galaxies. M84 may also exhibit a biconical structure, but the evidence in that object is less clear. Two other galaxies, NGC 4036 and NGC 4258, have structures that could plausibly be termed “linear.” None of the remaining 10 LINERs show this kind of morphology. Our attempt to find a link between LINERs and AGNs through this avenue has therefore given a positive result in only one, or at most four, cases. In NGC 1052, which already has various known AGN features, the cones are indeed aligned with the radio structure, as in Seyferts. Similarly, the possible biconical gas structure in M84, if real, would be roughly aligned with the axis of its radio jets (Birkinshaw & Davies 1985). Obviously, in the other objects we cannot search for alignment of the complex emission line structures with radio structures. Nonetheless, it will be interesting to see in the future whether or not elongated radio structures are common in LINERs.

Second, there is no clear difference in emission-line morphology between the UV-dark and UV-bright LINERs, but rather, there is a large variety from object to object. On the other hand, there is clear evidence for obscuration of the nucleus by clumps and lanes of dust in all of the clearly UV-dark objects, but not in the UV-bright ones. We conclude that foreground obscuration by nuclear dust is the cause of the non-detection of a central UV



point source in these LINERs, if such a source is present. In the one possible exception, NGC 4258, the detected but weak central UV source may be attenuated by dust mixed with the molecular gas in the masing disk that is known to exist on the line of sight to the nucleus. Although our sample is small and statistically incomplete, one may speculate that this is the reason that 75% of LINERs are UV-dark (Maoz et al. 1995; Barth et al. 1998) — that is, that all LINERs are photoionized by a central UV source, whose nature is of yet unknown, but that this source is obscured by circumnuclear dust in 75% of the cases.

In the same vein, we have found no evidence for obscuration by toroidal structures on smaller scales (which would produce the ionization cones we have generally failed to find), nor signs of a central source with “gaps” in the gas morphology hypothesized by Eracleous et al. (1995) in their duty-cycle picture. Nor do we find clear signs of outflows and shock-like morphologies, although there are hints of structures that may turn out to be related to such phenomena, if studied with deeper images at higher resolution. If, as the above results suggest, all LINERs have a central UV source with a photon flux of the right order of magnitude to power the observed emission line spectrum, then shocks are not needed to explain the excitation of the emission-line gas.

Our sample contains similar numbers of so-called LINER 1.9s, i.e., LINERs with weak broad H $\alpha$  emission, and LINER 2s, in which such broad lines have not been detected. The relative numbers of these two types among the LINER population are similar to the relative numbers of Seyfert 1 and Seyfert 2 galaxies (Ho et al. 1997b), and this may be another clue to a relation between LINERs and higher-luminosity AGNs. We find, however, no obvious differences in the emission line morphologies of the two LINER types. This is contrary to Seyferts, where the line morphologies of Seyfert 1s are more compact (Pogge 1989b; Schmitt & Kinney 1996), suggestive of a geometry in which the central engine and broad-line region are viewed unobscured along the axis of an obscuring torus. A caveat to this point is that the above study has compared Seyfert 1s and 2s, rather than 1.9s and 2s, and this distinction may be important.

One can imagine a number of physical reasons for the differences in the morphologies of LINERs and Seyferts. LINERs may, as a general rule, lack the toroidal collimating structures postulated in Seyferts. Alternatively, they may generally lack the relativistic jets that are often coaligned with extended emission structures in Seyferts. The jet/emission-line region alignment in Seyferts is thought to arise because both jets and ionizing radiation are collimated by related structures, or because the jet opens a path through the interstellar medium for ionizing photons to follow, or because the jet itself excites the line emission. Among our sample, this explanation cannot apply to M87, which has a conspicuous jet, yet no linear emission-line structure, either coincident with the jet or elsewhere.

Another possible explanation for the difference between LINERs and Seyferts is a deficit of circumnuclear gas or of ionizing photons in LINERs on the larger scales where linear structures appear in Seyferts. However, all Seyferts with extended narrow-line regions that have been imaged at *HST* resolution to date show that the collimated linear structures and cones persist all the way to the smallest angular scales probed (NGC 1068: Axon et al. 1998; NGC 4151: Evans et al. 1993; NGC 5252: Tsvetanov et al. 1996), and this is also what we have found in the biconical emission of the LINER NGC 1052. On the other hand, one might argue that these objects were preselected to have the narrowest and brightest extended narrow-line regions, and do not represent the Seyfert population as a whole. Finally, we note that the absence of linear emission-line structures in LINERs do *not* preclude them from being AGNs. Indeed, many of the LINERs in our sample have radio jets and/or broad-line regions, features that are considered characteristic of nuclear activity in more powerful objects. While linear emission-line features are found in many powerful AGNs, they are by no means a defining characteristic of the class.

A further point that has interesting physical and practical implications is that, when imaged at *HST* resolution, LINERs do not reveal simple disk-like gas structures, but rather more complex geometries. This implies that the kinematics of the circumnuclear gas are also likely to be quite complicated and could lead astray the interpretation of kinematic measurements aimed at determining the central black hole masses. Of special interest is the morphology of the line-emitting gas in the innermost regions close to the nucleus. In most of the cases in our sample, there is no indication of a small-scale disk, even if such a disk exists on larger scales. The kinematics of the gas at small radii, therefore, is unlikely to be governed predominantly by rotation. Indeed, recent *HST* spectroscopy of several galactic nuclei shows that the ionized gas has velocity dispersions that are large even in the innermost regions, as opposed to the circular velocity field expected from a cold gas disk. For example, the *HST FOS* emission-line spectra of the nuclear ionized gas disk in M87 (Harms et al. 1994; Macchetto et al. 1997) show line widths of  $\sigma \approx 500 \text{ km s}^{-1}$  at projected radii of  $0''.2$  to  $0''.6$  where the rotational velocity is  $500 - 600 \text{ km s}^{-1}$  (see Figure 5 of Macchetto et al. 1997). A similar trend is seen in NGC 4261 (Ferrarese, Ford, & Jaffe 1996): at a deprojected distance of  $\sim 0''.2$  from the nucleus, the gas disk shows  $v/\sigma \approx 1$ . Finally, the nuclear ionized gas disk of M84 observed by Bower et al. (1998) also displays large nonrotational motions near the center.

It is puzzling how gas in such a disturbed kinematic state within such a small ( $\sim 10^3 \text{ pc}^3$ ) volume can avoid settling into a cool, rotationally-dominated disk. The clumpy gas filaments will collide with each other at supersonic velocities of order  $100\text{--}200 \text{ km s}^{-1}$  on a dynamical time scale, which at a distance of  $5 \text{ pc}$  from a  $10^8 M_\odot$  central mass is  $10^5 \text{ yr}$ . This is much shorter than the expected lifetime of the AGN or the nuclear starburst, but

much longer than the cooling time, which, for free-free emission, is of order 100 yr for gas with a density  $10^5 \text{ cm}^{-3}$  that has been heated to  $\sim 10^6 \text{ K}$  by collisions.

## 5. Summary

We have presented narrowband ( $[\text{O III}]\lambda 5007$  and  $\text{H}\alpha + [\text{N II}]$ ) emission-line images of 14 galaxies with LINER nuclei. Most of these data have not been previously published, and this is the first time that the narrow-line regions of a significant number of LINERs are studied at *HST* resolution. The objects in our sample include representatives of the various subclasses of LINERs that have emerged in recent years: “type 1.9” and “type 2,” UV-bright and UV-dark, objects with starburst-dominated or AGN-dominated UV spectra.

Our main observational findings are as follows.

1. The narrow-line regions of nearby LINERs are resolved by *HST*, with much of the line emission coming from regions with sizes of 10–100 pc.
2. In general, the emission-line morphology is complex and disordered, with varying contributions from a compact core, a disk, clumps, and filaments. We find no obvious distinctions in morphologies among the various LINER subclasses.
3. In only one object, NGC 1052, possibly two if we include M84, have we found clear evidence for an ionization cone analogous to those seen in Seyfert galaxies. The ionization cone of NGC 1052 is well-aligned with its radio structure. Two or three other objects have morphologies that can perhaps be termed “linear.”
4. Obscuration of the nucleus by circumnuclear clumps of dust is fairly ubiquitous in the UV-dark LINERs but absent in the UV-bright ones.

These findings lead us to the following conclusions. First, the data are consistent with a picture in which most or all LINERs are objects that are photoionized by a central UV source, even when the central source is not visible directly. As discussed in §1, Maoz et al. (1998) showed that in UV-bright LINERs, the extreme-UV flux, based on a reasonable extrapolation from the UV, is of the right magnitude to account for the observed  $\text{H}\alpha$  in a photoionization scenario. Any mild foreground extinction, which appears to be common based on the images presented here, would only strengthen this conclusion. Hence, the line emission UV-bright LINERs is likely to be powered by photoionization. Our results suggest that the UV visibility of the nucleus is determined simply by the circumnuclear dust

morphology along our line of sight. This suggestion is reinforced by the the anti-correlation between UV brightness on the one hand, and galaxy inclination and Balmer decrement on the other, found by Barth et al. (1998). A similar inclination effect has been seen in Seyfert galaxies at visible (Keel 1980) and X-ray wavelengths (Lawrence & Elvis 1982). Thus, the fact that the majority of the LINERs in optically-selected samples are UV dark (Maoz et al. 1995; Barth et al. 1998) does not necessarily imply that these objects are excited by processes other than photoionization (e.g., shocks; Dopita & Sutherland 1995) or that they are in an “off” state (Eracleous et al. 1995). There is also no correspondence between UV darkness and the absence of broad lines in LINERs, which one might expect in a duty-cycle scenario when the continuum source is turned off. Moreover, the UV spectra of the nuclei of individual LINERs have so far failed to reveal the emission-line signatures predicted by shock models. This result argues against these alternative explanations for the UV-bright/dark dichotomy. If, as our results suggest, UV-dark LINERs appear as such only because of foreground extinction, then it is plausible to conclude that all LINERs harbor a source of ionizing radiation, and hence that their line-emitting gas is powered by photoionization.

In passing, we note that in the non-elliptical galaxies in our sample, the circumnuclear dust, though patchy and sometimes chaotic in appearance, generally lies in a preferred plane. The position angle of this plane coincides remarkably closely to the direction of the major axis of the large-scale galactic disk (data compiled in Ho et al. 1997a). This explains why the UV visibility of the nuclei correlates with the inclinations of the host galaxies (Barth et al. 1998) despite the fact that the obscuration, as seen in our images, actually occurs on much smaller scales.

Second, whatever the nature of the central source in a LINER, be it an accretion flow onto a black hole, a compact star cluster, or a combination of the two, it is not generally revealed by the narrowband images we have obtained. The one LINER that shows a clear Seyfert-like ionization cone, NGC 1052, does have additional AGN characteristics: weak broad wings in its  $H\alpha$  emission profile (Ho et al. 1997b), a hidden broad-line region (Barth et al. 1999a), a radio jet and compact, flat-spectrum core (Wrobel 1984), and a nonthermal hard X-ray spectrum (Guainazzi & Antonelli 1999; Weaver et al. 1999). On the other hand, many of the other LINERs which have AGN features, such as NGC 4579, M81, and M87, show no evidence for ionization cones in our images.

Finally, we have pointed out that the complex gas morphologies revealed by our images suggest caution in interpreting the gas kinematics in the innermost regions of these objects, for example, in searches for, and mass measurements of, central black holes.

This work was supported by grant GO-06436.01-95A from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555. Undergraduate research assistant S. Benfer (Ohio Wesleyan) helped with the initial reductions of our GO imaging data. D.M. acknowledges support by a grant from the Israel Science Foundation. L.C.H. is grateful to Sandra Faber for bringing to his attention the issue concerning the kinematics of the compact narrow-line regions in LINERs that we discussed at the end of §3.2.

## REFERENCES

- Allen, M. G., Koratkar, A. P., & Dopita, M. A. 1999, BAAS, 194, 4901
- Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 621
- Awaki, H. 1999, Advances in Space Research, 23 (5-6), 837
- Axon, D. J., Marconi, A., Capetti, A., Maccetto, D. F., Schreier, E., & Robinson, A. 1998, A&A, 496, L75
- Barth, A. J., Filippenko, A. V., & Moran, E. C. 1999a, ApJ, 515, L61
- Barth, A. J., Filippenko, A. V., & Moran, E. C. 1999b, ApJ, in press (astro-ph/9905290)
- Barth, A. J., Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1998, ApJ, 496, 133
- Barth, A. J., Reichert, G. A., Filippenko, A. V., Ho, L. C., Shields, J. C., Mushotzsky, R. F., & Puchnarewicz, E. M. 1996, AJ, 112, 1829
- Barth, A. J., Tran, H., Brotherton, M. S., Filippenko, A. V., Ho, L. C., van Breugel, W., Antonucci, R., & Goodrich, R. W. 1999c, ApJ, in press (astro-ph/9907269)
- Biretta, J. A., et al. 1996, WFPC2 Instrument Handbook (Baltimore: STScI)
- Birkinshaw, M. & Davies, R. L. 1985, ApJ, 291, 32
- Boksenberg, A., et al. 1992, A&A, 261, 393
- Bower, G. A., Heckman, T. M., Wilson, A. S., & Richstone, D. O. 1997, ApJ, 483, L33
- Bower, G. A., et al. 1998, ApJ, 492, L111
- Cecil, G., Wilson, A. S., Tully, R. B. 1992, ApJ, 390, 365
- Cecil, G., Wilson, A. S., & DePree C. 1995, ApJ, 440, 181
- Cecil, G., Morse, J. A., & Veilleux, S. 1995, ApJ, 452, 613
- Crane, P., et al. 1993, AJ, 106, 1371
- Devereux, N., Ford, H., & Jacoby, G. 1997, ApJ, 481, L71

- Dickey, J. M. & Lockman, F. J. ARA&A, 28, 215
- Dopita, M. A. & Sutherland, R. S. 1995, ApJ, 455, 468
- Eracleous, M., Livio, M., Binette, L. 1995, ApJ, 445, L1
- Eracleous, M., Koratkar, A., Leitherer, C., & Ho, L. 1996, The Physics of LINERs in View of Recent Observations (San Francisco: ASP)
- Evans, I. N., Tsvetanov, Z., Kriss, G. A., Ford, H. C., Caganoff, S., & Koratkar, A. P. 1993, ApJ, 417, 82
- Fabbiano, G., Fassnacht, C., & Trinchieri, G. 1994, ApJ, 434, 67
- Fabbiano, G. & Juda, J. Z. 1997, ApJ, 476, 666
- Fabbiano, G., Kim, D.-W., & Trinchieri, G. 1992, ApJS, 80, 531
- Ferrarese, L., Ford, H. C., & Jaffe, W. 1996, ApJ, 470, 444
- Filippenko, A. V. & Sargent, W. L. W. 1985, ApJS, 57, 503
- Filippenko, A. V. & Terlevich, R. 1992, ApJ, 397, L79
- Fosbury, R. A. E., Melbold, U., Goss, W. M., & Dopita, M. A. 1978, MNRAS, 183, 549
- Freedman, W. L., et al. 1994, ApJ, 427, 628
- Ford, H. C., et al. 1994, ApJ, 435, L27
- Gabel, J. R., Bruhweiler, F. C., Crenshaw, D. M., Kraemer, S. B., & Miskey, C. L. 1999, BAAS, 194, 4902
- Guainazzi, M. & Antonelli, L. A. 1999, MNRAS, 304, L15
- Haniff, C. A., Wilson, A. S., & Ward, M. J. 1988, ApJ, 334, 104
- Harms, R. J., et al. 1994, ApJ, 435, L35
- Heckman, T. M. 1980, A&A, 87, 152
- Herrnstein, J. R., et al. 1999, Nature, in press (astro-ph/9907013)
- Ho, L. C. 1999, ApJ, 516, 672
- Ho, L. C., et al. 2000b, in preparation
- Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1995, ApJS, 98, 477
- Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1996, ApJ, 462, 183
- Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997a, ApJS, 112, 315
- Ho, L. C., Filippenko, A. V., Sargent, W. L. W., & Peng, C. Y. 1997b, ApJS, 112, 391
- Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 2000a, in preparation

- Ho, L. C., Ptak, A., Terashima, Y., Kunieda, H., Serlemitsos, P. J., Yaqoob, T., & Koratkar, A. P. 1999, *ApJ*, in press (astro-ph/9905013)
- Holtzman, J. A., et al. 1995, *PASP*, 107, 1065
- Keel, W. C. 1980, *AJ*, 85, 198
- Keel, W. C. 1983a, *ApJ*, 268, 632
- Keel, W. C. 1983b, *ApJ*, 269, 466
- Koratkar, A. P., Deustua, S., Heckman, T. M., Filippenko, A. V., Ho, L. C. & Rao, M. 1995, *ApJ*, 440, 132
- Koski, A. T. & Osterbrock, D. E. 1976, *ApJ*, 203, L49
- Krist, J. & Hook, R. 1997, *The Tiny Tim User's Guide*, Version 4.4 (Baltimore: STScI)
- Lawrence, A. & Elvis, M. 1982, *ApJ*, 256, 410
- Macchetto, F., Marconi, A., Axon, D. J., Capetti, A., Sparks, W. B., & Crane, P. 1997, *ApJ*, 489, 579
- Maoz, D., Filippenko, A. V., Ho, L. C., Rix, H.-W., Bahcall, J. N., Schneider, D. P., & Macchetto, F. D. 1995, *ApJ*, 440, 91
- Maoz, D., Filippenko, A. V., Ho, L. C., Macchetto, F. D., Rix, H.-W., & Schneider, D. P. 1996, *ApJS*, 107, 215
- Maoz, D., Koratkar, A. P., Shields, J. C., Ho, L. C., Filippenko, A. V., & Sternberg, A. 1998, *AJ*, 116, 55
- Miyoshi, M., Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., & Inoue, M. 1995, *Nature*, 373, 127
- Nandra, K., George, I. M., Mushotzky, R. F., Turner, T. J., & Yaqoob, T. 1997, *ApJ*, 477, 602
- Nicholson, K. L., Reichert, G. A., Mason, K. O., Puchnarewicz, E. M., Ho, L. C., Shields, J. C., & Filippenko, A. V. 1998, *MNRAS*, 300, 893
- Pogge, R. W. 1989a, *ApJ*, 345, 730
- Pogge, R. W. 1989b, *ApJS*, 71, 433
- Pogge, R. W. 1992, in *Astronomical CCD Observing and Reduction Techniques*, ed. S. B. Howell (San Francisco: ASP), 195
- Pogge, R. W. & Martini 2000, in preparation
- Ptak, A., Serlemitsos, P., Yaqoob, T., & Mushotzky, R. F. 1999, *ApJS*, 120, 179
- Sankrit, R., Sembach, K.R., & Canizares, C.R. 1999, *ApJ*, in press (astro-ph/9907406)

- Sargent, W. L. W., Young, P. J., Boksenberg, A., Shortridge, K., Lynds, C. R., & Hartwick, F. D. A. 1978, *ApJ*, 221, 731
- Schmitt, H. R. & Kinney, A.L. 1996, *ApJ*, 463, 498
- Serlemitsos, P., Ptak, A., & Yaqoob, T. 1996, in *The Physics of LINERs in View of Recent Observations*, ed. M. Eracleous, A. Koratkar, C. Leitherer, & L. Ho (San Francisco: ASP), 70
- Shields, J. C. 1992, *ApJ*, 399, L27
- Stauffer, J. R. 1982, *ApJ*, 262, 66
- Terashima, Y. 1999, *Advances in Space Research*, 23 (5-6), 851
- Terashima, Y., Ho, L. C., Ptak, A. F., Mushotzky, R. F., Serlemitsos, P. J., Yaqoob, T., & Kunieda, H. 1999, *ApJ*, submitted
- Terashima, Y., Kunieda, H., Misaki, K., Mushotzky, R. F., Ptak, A., & Reichert, G. A. 1998, *ApJ*, 503, 212
- Terlevich, R. & Melnick, J. 1985, *MNRAS*, 213, 841
- Tsvetanov, Z., Morse, J. A., Wilson, A. S., & Cecil, G. 1996, *ApJ*, 458, 172
- Tully, R. B. 1988, *Nearby Galaxies Catalog* (Cambridge: Cambridge Univ. Press)
- van Dokkum, P. G. & Franx, M. 1996, *AJ*, 110, 2027
- Watson, W. D. & Wallin, B. K. 1994, *ApJ*, 432, L35
- Weaver, K. A., Wilson, A. S., Henkel, C., & Braatz, J. A. 1999, *ApJ*, 520, 130
- Wiklind, T. & Henkel, H. 1990, *A&A*, 227, 394
- Wilkes, B. J., Schmidt, G. D., Smith, P. S., Mathur, S., & McLeod, K. K. 1995, *ApJ*, 455, L13
- Wilson, A. S. & Tsvetanov, Z. I. 1994, *AJ*, 107, 1227
- Wilson, A. S., Braatz, J. A., Heckman, T. M., Krolik, J. H., & Miley, G. K. 1993, *ApJ*, 419, L61
- Wrobel, J. M. 1984, *ApJ*, 284, 531
- Zirbel, E. L. & Baum, S. A. 1998, *ApJS*, 114, 177



**Figure 1a-d:** Narrowband PC1 images and dust maps. For each galaxy we show the continuum-subtracted  $H\alpha+[N\ II]$  image on the left, and on the right either the  $(V - I)$  color map or the unsharp mask of the F547M frame if no  $I$ -band image is available. Darker shades denote regions of dust absorption. Each panel shows a  $10'' \times 10''$  segment of the image centered on the nucleus (oriented with North up, East to the left), and with a scale bar in the lower left corner of each emission-line images showing 100 pc projected at the galaxy’s distance (see Table 1). The contrast of the emission-line images is chosen to emphasize the faint circumnuclear emission regions.

**Figure 1e:** Narrowband WF3 images of the central  $30''$  of NGC 3031, shown like the others in Figure 1a-d.  $H\alpha+[N\ II]$  emission is on the left, and the unsharp residual map is on the right. The scale bar in the lower left shows 100 pc at the distance of NGC 3031 (Table 1).

**Figure 2:** Narrowband PC1 images of the central  $15''$  of NGC 1052. Left panel: F658N image (without continuum subtraction); Right panel: normalized unsharp residual map of the same. The residual map shows emission as bright and absorption (presumably dust) as dark. Each panel shows of NGC 1052, and the scale bar indicates 100 pc. The axis of the VLA radio jet (Wrobel 1984) is shown with the dashed line.

**Figure 3a:** Continuum-subtracted PC1  $[O\ III]\lambda 5007$  emission-line images (left) of NGC 4258, NGC 4579, and NGC 5005, shown alongside of “excitation maps” of the  $H\alpha+[N\ II]/[O\ III]\ \lambda 5007$  ratio (right). The scaling and orientation follow that in Figures 1a-d.

**Figure 3b:** Continuum-subtracted PC1  $[O\ III]\lambda 5007$  images of NGC 4192 (left) and NGC 4569 (right). For these galaxies the “excitation maps” are extremely noisy and contain no useful information. The scaling and orientation are as in Figure 3a.

**Figure 4:** Montage of PC1 images of NGC 4258 showing (left-to-right, top-to-bottom) F547M,  $[O\ III]\lambda 5007$  emission, F300W, and F218W. All maps show the central  $10''$  of the galaxy centered on the active nucleus. The scaling and orientation are as in Figures 1–3.

This figure "fig1a.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9910375v1>

This figure "fig1b.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9910375v1>

This figure "fig1c.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9910375v1>

This figure "fig1d.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9910375v1>

This figure "fig1e.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9910375v1>

TABLE 1  
SAMPLE GALAXIES AND THEIR BASIC PROPERTIES

Galaxy	Hubble Type <sup>a</sup>	$v_{\odot}$ <sup>a</sup> (km s <sup>-1</sup> )	Distance <sup>b</sup> (Mpc)	Scale (pc/'')	$B_T$ <sup>a,c</sup> (mag)	AGN Class <sup>d</sup>	$A_V$ <sup>e</sup> (mag)	Central UV Flux <sup>f</sup>
NGC 404	SA(s)0-:	- 46	2.4	12	11.21	L2	0.28	$1.2 \times 10^{-15}$ [1]
NGC 1052	E4	1499	17.8	86	11.41	L1.9	0.16	$1.5 \times 10^{-16}$ [2]
NGC 3031 (M81)	SA(s)ab	- 37	3.6	18	7.89	S1.5	0.22	$1.5 \times 10^{-15}$ [1]
NGC 3718	SB(s)a pec	993	17.0	82	11.59	L1.9	0.06	$< 7.0 \times 10^{-18}$ [3]
NGC 3998	SA(r)0?	1049	21.6	105	11.61	L1.9	0.06	$> 9.8 \times 10^{-15}$ [4]
NGC 4036	SA0-	1396	24.6	119	11.57	L1.9	0.10	$< 2.0 \times 10^{-17}$ [5]
NGC 4192 (M98)	SAB(s)ab	- 142	16.8	81	10.95	L1.9	0.14	$< 7.0 \times 10^{-18}$ [3]
NGC 4258 (M106)	SAB(s)bc	450	7.2	33	9.10	S1.9	0.06	$7.0 \times 10^{-17}$ [6]
NGC 4374 (M84)	E1	956	16.8	81	10.09	L2	0.14	$< 5.1 \times 10^{-17}$ [7]
NGC 4486 (M87)	E4+pec	1282	16.8	81	9.59	L2	0.13	$1.7 \times 10^{-15}$ [8]
NGC 4569 (M90)	SAB(rs)ab	- 235	16.8	81	10.26	T2	0.13	$1.0 \times 10^{-14}$ [1]
NGC 4579 (M58)	SAB(rs)b	1521	16.8	81	10.48	S1.9	0.13	$3.3 \times 10^{-16}$ [1]
NGC 4594 (M104)	SA(s)a spin	1088	20.0	97	8.98	L2	0.20	$< 1.2 \times 10^{-16}$ [1] <sup>g</sup>
NGC 5005	SAB(rs)bc	948	21.3	103	10.61	L1.9	0.06	$< 7.0 \times 10^{-18}$ [3]

<sup>a</sup> The information was taken from the compilation of Ho et al. (1997a).

<sup>b</sup> The distances, with three exceptions, were drawn from Tully (1988), who assumes  $H_0 = 75$  km s<sup>-1</sup> Mpc<sup>-1</sup> (see §5.2 of Ho et al. 1997a for further details). The exceptions are NGC 3031 (Freedman et al. 1994) and NGC 4258 (Herrnstein et al. 1999).

<sup>c</sup> The total apparent blue magnitude of the galaxy.

<sup>d</sup> Classification according to the ratios of the narrow emission lines and the presence of broad emission lines (see Ho et al. 1997a, b for details). S = Seyfert, L = LINER, T = transition object (intermediate between LINER and H II nucleus). Objects with weak, broad H $\alpha$  emission present are denoted as type “1.9,” while those without broad H $\alpha$  emission are denoted as type “2.”

<sup>e</sup> Galactic visual extinction. Computed from the H I column densities of Dickey & Lockman (1990), assuming  $N_{\text{H}}/A_V = 1.9 \times 10^{21}$  cm<sup>-2</sup> mag<sup>-1</sup>.

<sup>f</sup> Measured UV flux density ( $f_{\lambda}$ ), or upper limit, in units of erg cm<sup>-2</sup> s<sup>-1</sup> Å<sup>-1</sup>, at 2200 Å, except for NGC 3998, for which measurement is at 1730 Å. Numbers in square brackets give the reference, as follows: (1) Maoz et al. 1998; (2) Maoz et al. 1998; (3) Maoz et al. 1998; (4) Fabbian et al. 1994; (5) Dickey et al. 1993; (6) Ho et al. 1997a; (7) Maoz et al. 1998; (8) Maoz et al. 1998.

6661-120-07 JAS/601664d-oncr:AJXP

This figure "fig2.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9910375v1>



TABLE 2  
LIST OF OBSERVATIONS AND EXPOSURE TIMES

Galaxy	Narrow-Band Filters <sup>a</sup>			Broad-Band Filters <sup>a</sup>			Program <sup>b</sup> (GO/GTO)
	F502N	F656N	F658N	F547M	F791W	F814W	
NGC 404	...	1700 s	...	350 s	...	480 s	5999,6871
NGC 1052	...	...	1900 s	...	...	...	6286
NGC 3031	...	1800 s	...	90 s	...	...	5986
NGC 3718	...	...	4200 s	300 s	720 s	...	6436,5419
NGC 3998	...	...	1660 s	240 s	100 s	...	5924
NGC 4036	...	...	2800 s	300 s	...	...	5419,6785
NGC 4192	5000 s	2600 s	...	720 s	720 s	...	6436
NGC 4258	2300 s	...	2300 s	1160 s	...	...	5123
NGC 4374	...	...	2600 s	1200 s	...	520 s	6094
NGC 4486	...	...	2700 s	800 s	...	...	5122
NGC 4569	1000 s	800 s	...	726 s	726 s	...	6436
NGC 4579	3200 s	...	1400 s	726 s	726 s	...	6436
NGC 4594	...	...	1600 s	940 s	...	420 s	5512,5924
NGC 5005	2400 s	...	1400 s	230 s	720 s	...	6436,6519

<sup>a</sup> Exposure times are given in the appropriate column for each object and filter.

<sup>b</sup> The *HST* program number under which the observations were carried out. GO-6436 is our own observing program; data from other programs were retrieved from the *HST* public archive.

This figure "fig3a.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9910375v1>

This figure "fig3b.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9910375v1>

TABLE 3  
OBSERVED LINE FLUXES AND RATIOS AS MEASURED FROM THE IMAGES

Galaxy	Nuclear <sup>a</sup>			Circumnuclear <sup>a</sup>			Total <sup>a</sup>			Aperture Radii	
	H $\alpha$	[O III]	[O III]/H $\alpha$	H $\alpha$	[O III]	[O III]/H $\alpha$	H $\alpha$	[O III]	[O III]/H $\alpha$	Nuclear	Total
NGC 404	4.80	...	...	35.73	...	...	40.53	...	...	0'23	4'0
NGC 3718	2.99	...	...	4.24	...	...	7.23	...	...	0'23	4'0
NGC 3998	66.45	...	...	80.25	...	...	146.70	...	...	0'23	4'0
NGC 4036	2.52	...	...	44.25	...	...	46.76	...	...	0'23	4'0
NGC 4192	0.78	0.11	0.13	4.16	1.22	0.29	4.94	1.32	0.27	0'15	0'52 $\times$ 0'43 <sup>b</sup>
NGC 4258	12.18	11.67	0.96	59.16	74.85	1.27	71.34	86.52	1.21	0'23	6'0
NGC 4374	4.44	...	...	40.97	...	...	45.41	...	...	0'23	4'0
NGC 4486	14.48	...	...	73.03	...	...	87.51	...	...	0'23	4'0
NGC 4569	43.78	5.43	0.12	95.72	1.88	0.02	139.50	7.31	0.05	0'23	2'5
NGC 4579	17.72	6.54	0.37	43.23	2.45	0.06	60.95	8.99	0.15	0'23	2'5
NGC 4594	24.40	...	...	51.68	...	...	76.08	...	...	0'23	4'0
NGC 5005	6.73	0.39	0.06	113.47	20.97	0.18	120.20	21.36	0.18	0'23	2'28 $\times$ 3'0 <sup>b</sup>

<sup>a</sup> All fluxes are integrated over the filter bandpass and are given in units of  $10^{-16}$  erg s<sup>-1</sup> cm<sup>-2</sup>.

<sup>b</sup> Rectangular aperture.

This figure "fig4.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9910375v1>